Chapter 20. Upgrade of Other Technical Systems

20.1 Magnets

D. Harding

The properties of the magnets themselves do not impose a limit to running the Fermilab Main Injector at its design rate of 240 GeV/sec with a 1.467 second cycle time. Shorter cycle times, down to as little as one second, appear viable, though tests should be considered before running at a ramp rate significantly faster than the design. We address that highest ramp and repetition rate here; anything between that and the design is also good.

It should be noted that there are about two dozen different kinds of magnets in the Main Injector complex. We concentrate here on the most numerous of them, as they would require the largest effort to modify.

20.1.1. Voltage to Ground

The doubling of the ramp rate required to execute a one second cycle time doubles the inductive voltage across each magnet, the dominant factor for the ring magnets.

1. Dipoles. The typical operating voltage to ground for the dipoles with the nominal ramp ranges up to 500 V and the coil to through bus reaches 1000 V. In fault conditions the coil to ground voltage can reach 1000 V. Doubling the ramp rate approximately doubles these numbers with the existing bus configuration.

   The magnet insulation was designed to withstand a DC voltage of 5000 V to ground and 10,000 V between coil and through bus, and in production every magnet was tested at these voltages with a limit of <5 µA leakage current. In practice the current was below the 0.05 µA limit measurable with the test equipment.

   AC operation imposes more stringent conditions on devices due to the potential for partial discharge. In September 2000 Chez Jach measured one spare MI dipole and found an extinction voltage of about 535 V. While this suggests that the magnets are safe under current operating conditions, it may be worth looking more closely if a higher ramp rate is desired. Examining more than a single sample would give a better picture of the distribution of behavior across the ring. Localizing the discharge might reassure us of the triviality of the location or suggest a relatively uncomplicated improvement to extend the magnet lifetime.

2. Quadrupoles. In order to double the ramp rate, additional quadrupole power supplies would be necessary. Spacing them around the ring leaves the voltage to ground as it is now. Corona tests on old and new Main Injector quadrupoles would be useful.

3. Sextupoles. The sextupoles were tested to 1500 V during production.

4. <u>Other magnets.</u> All other magnets run in such short strings that the total voltage to ground does not become an issue even with the higher ramp rate.

20.1.2. Magnet Field Quality

We do not expect the field shape due to the magnet steel to vary with ramp rate during acceleration, although a small change in the strength and sextupole component of the dipole field at injection is possible. (See the Fermilab Main Injector Technical Design Handbook section 3.1, page 15 and the references therein.) These changes are small enough to be easily accommodated by small operational changes in the dipole and sextupole bus currents.

20.1.3. Beam Tube Eddy Currents

Eddy currents in the beam tubes will double with the doubling of the ramp rate, with two effects - heating and field distortion.

The heating is negligible at these ramp and repetition rates; the beam tube is in intimate contact with the pole, which serves as an excellent heat sink.

The field distortion is primarily the generation of a sextupole component. The sextupole system, magnets and power supply, were designed to compensate for the sextupole from the saturation of the dipole magnets at 150 GeV. The increased effect of the eddy currents in a 120 GeV ramp is minimal compared to that saturation (MI-Note 0100) so the present sextupole system can compensate adequately.

20.1.4. Magnet Heating

The ramp rate is not yet high enough to induce significant eddy current heating in the magnets. All the ring and beam line magnets are designed to run DC at their peak current, so even if the rms power dissipation increased substantially they would not suffer as long as the water system continues to provide cooling water at the nominal pressure and temperature. The shorter cycle time actually decreases the rms power compared to the design antiproton production cycle, let alone the design slow spill cycle, so cooling should not be an issue.
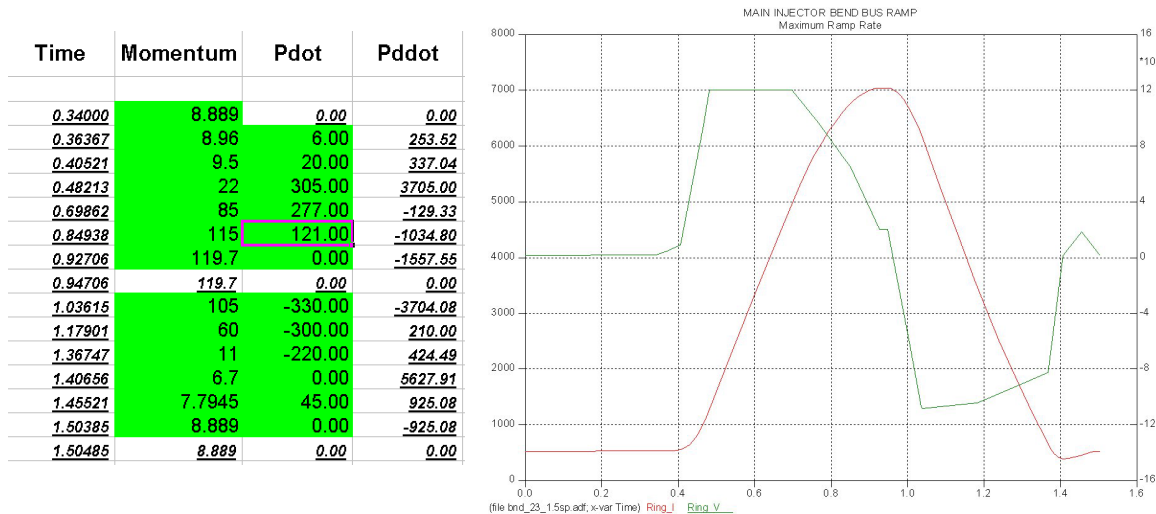
20.2 Power Supplies

D. Wolff

20.2.1 Present Power Supply Capability

The available voltage from the power supply rectifier stations determines the limit on the ramp rate of the Main Injector. The following table lists the maximum voltage available for each bus:

BUS	RAMP	INVERT
Bend Bus	12.0 kV	-10.8 kV
QD Bus	2.9 kV	-2.6 kV
QF Bus	2.9 kV	-2.6 kV

Given these limitations, a ramp with a total cycle time of about 1.5 seconds was developed, (The goal is 1.533 seconds.) while minimizing changes to the existing $23 ramp, the one for 6-Booster batch injection for NuMI. Figure 20.1 and its associated table show the segment-by-segment ramp description and the resulting bend bus power supply waveforms.

Time	Momentum	Pdot	Pddot
0.34000	8.889	0.00	0.00
0.36367	8.96	6.00	253.52
0.40521	9.5	20.00	337.04
0.48213	22	305.00	3705.00
0.69862	85	277.00	-129.33
0.84938	115	121.00	-1034.80
0.92706	119.7	0.00	-1557.55
0.94706	119.7	0.00	0.00
1.03615	105	-330.00	-3704.08
1.17901	60	-300.00	210.00
1.36747	11	-220.00	424.49
1.40656	6.7	0.00	5627.91
1.45521	7.7945	45.00	925.08
1.50385	8.889	0.00	-925.08
1.50485	8.889	0.00	0.00

Figure 20.1. Bend bus current and voltage waveform for 1.5 seconds cycle.

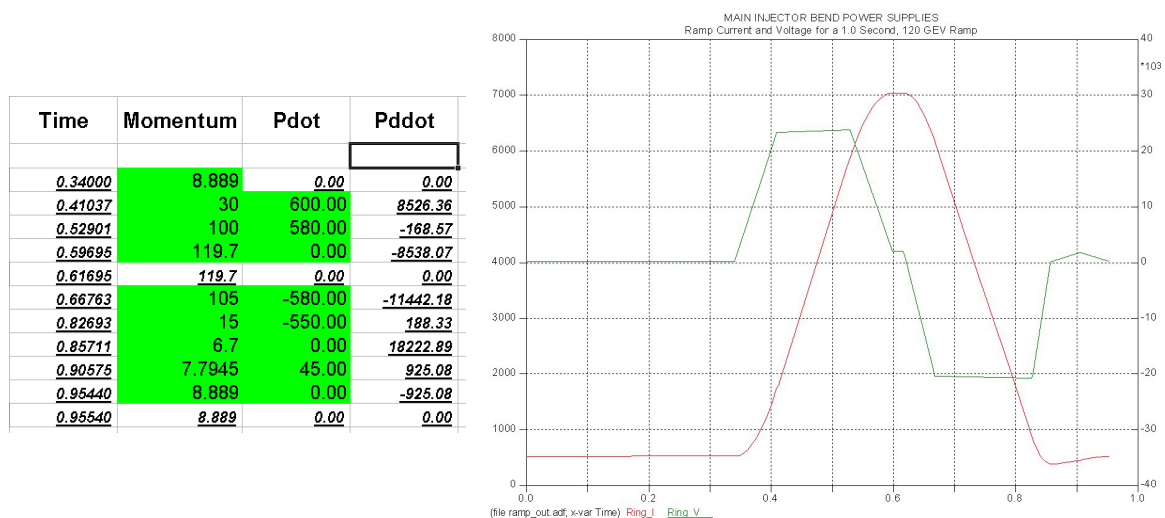The following is a list of the changes to the $23 ramp that were made to achieve this cycle time:

1. The injection time was reduced from 0.5 s to 0.34 s.
2. The 22 GeV ramping segment was increased from 240 GeV/s to 305 GeV/s.
3. The 85 GeV ramping segment was increased from 230 GeV/s to 277 GeV/s.
4. The flattop time was reduced from 98 ms to 20 ms.
5. The 105 GeV invert segment was increased from -300 GeV/s to -330 GeV/s.
6. The 60 GeV invert segment was increased from -280 GeV/s to -300 GeV/s.

While the above ramp cycle time of 1.5049 seconds meets the goal, the power supplies would be operating at their limits. During certain times of the year, particularly on hot summer days, the AC mains may sag and that could result in losing the exacting current

regulation required for successful accelerator operation. Studies should be performed to measure the voltage regulation margin in the power supply stations while operating with this new ramp. If the margin is considered too small, a fairly inexpensive solution exists. One power supply in each of the buses could be upgraded to gain a nominal increase in voltage output. Such a modification was completed a couple of years ago for one power supply in each of the quadrupole busses when it was determined that the power supplies were having trouble achieving the 1.5-second cycle rate required for antiproton stacking.

20.2.2. Power Supply Modifications Required to Operate at a 1.0 Second Cycle Rate

To operate at a 1.0-second cycle major modifications need to be made to the power supply system. Basically, twice as much voltage is needed for a 1.0-second ramp compared to the 1.5-second ramp. To accomplish this, we propose to add to every Main Injector service building two additional bend power supplies and one additional quadrupole power supply. This will double the operating voltage-to-ground on the bend bus but keep the quadrupole busses the same. Figure 20.2 and its associated table show the proposed ramp description and bend bus waveforms:

Time	Momentum	Pdot	Pddot
0.34000	8.889	0.00	0.00
0.41037	30	600.00	8526.36
0.52901	100	580.00	-168.57
0.59695	119.7	0.00	-8538.07
0.61695	119.7	0.00	0.00
0.66763	105	-580.00	-11442.18
0.82693	15	-550.00	188.33
0.85711	6.7	0.00	18222.89
0.90575	7.7945	45.00	925.08
0.95440	8.889	0.00	-925.08
0.95540	8.889	0.00	0.00

Figure 20.2. Bend bus current and voltage waveform for 1.0-second cycle.

For this ramp we needed to abandon the parabolas as defined in the present $23 ramp and allow the power supplies to ramp to their maximum voltage as fast as possible while still maintaining good voltage regulation. Whether the proton beam will behave well with such a ramp is unknown.

In addition to the power supplies themselves, the high-current DC bus, the AC feeders, the service buildings, and the Kautz Road substation will all need major modifications. The following summarizes the changes that are needed:

1. Main Injector service buildings:

* Buildings themselves need to be enlarged to accommodate two additional bend power supplies and one additional quadrupole power supply.
* Power supply transformers, pads, and additional feeder work need to be added outside each building.
* One additional high-current DC quadrupole bus (to the tunnel) will need to be installed at each building.

2. Main Injector Feeders:
   The number of power supply feeders will have to double. Sufficient duct bank space should be available in most areas around the ring. The bank by the MI 60 service building may need to be expanded.

3. Kautz Road Substation:
   * Two additional 345 kV transformers will be needed.
   * The substation building will need to be expanded to accommodate additional breakers and relaying equipment.
   * Two additional harmonic filters will need to be installed.

20.3. Mechanical and Utility

A. Chen

20.3.1 Mechanical & Utility Requirements

As the Main Injector repetition rate increases from 0.54 Hz to 0.65 Hz (the cycle time reduced from 1.867 s to 1.533 s), the change of total heat load in magnets is insignificant. The heat load for power supplies can still be handled by existing capacity at the service buildings, which have about 20% margin. However, the heat load due to the rf system upgrade will be increased dramatically as shown in Table 20.1. It becomes the main issue from the mechanical point of view.

Table 20.1. LCW requirements for RF System Upgrade

	Present	Upgraded
Flow rate for 95° F rf	2100 gpm	4000 gpm
Heat load for 95° F rf	3.3 MW	7.5 MW
Flow rate for 90° F cavity	730 gpm	1500 gpm
Heat load for 90° F cavity	0.5 MW	2.5 MW

To meet these requirements, it is necessary to upgrade the MI-60 pump room and most of present piping for rf power supplies and its cavity system. Meanwhile, MI cooling ponds have already been run at their full capacity so extra cooling pond area will be needed.

20.3.2 LCW System upgrade

20.3.2.1. MI60 Pump Room

a) 95° F LCW for rf power supplies:
Adding one more heat exchanger will increase the capacity from 6.6 MW to 9.9 MW. In order to fit the third heat exchanger into the fully occupied room, some modification of the building is necessary. This includes removing the swinging door, widening the garage door, and relocating pumps and manifolds. The four pumps would be upgraded to deliver the doubled flow rate.

b) 90° F LCW for rf cavities:
Its current heat exchanger has a design capacity of 3 MW. But it has served about 30 years and some channels are partially clogged so it may be necessary to replace it with a new one at the same or higher capacity in order to take the 2.5 MW load. (Currently the load is 0.5 MW.)

20.3.2.2. Piping

The flow rate for both the rf power systems and its cavity needs to be doubled. We can either run another pipe at the same size as the current ones or replace them with larger sizes. It will cost less to run another pipe as long as there is space for it. At the penetrations, it can only be done by replacing the existing 10-inch pipe with a larger pipe.

20.3.2.3. Cooling pond

The MI cooling ponds are almost running at their full capacity now. The 5 MW extra heat load will need extra cooling surface. We can either create a new pond of about 5 acres in the region of the MI or utilize existing Tevatron cooling ponds. The MI rf is close to the Tevatron Ring. It needs less than 1000 feet of piping to connect the MI rf LCW to Tevatron Pond 24. Pond 20, 21, 22, 23, 24 together can provide more than 5 acres of surface area with minor modification of their channels. These ponds are designed for the cooling needs of Tevatron Sector E, which has a very low heat load. However, it would cost about $400 K to construct 5 acres new pond at the MI region. The costs of their auxiliary systems are the same in either way.

20.4. Kickers

C. Jensen

Most of the MI kickers were designed to handle a 1.467 second cycle time for antiproton production, so changing to a 1.5 second cycle time is a non-issue for all but the MI-60 (NuMI) 6-batch extraction kickers and the MI-52 (120/150 GeV proton extraction) 6-batch kickers. For the NuMI kickers it is a simple matter to purchase a larger charging

supply to charge the pulse-forming network (PFN) in a shorter time (currently 1.833 second cycle time). For the MI-52 kickers the problem is more fundamental. While a larger charging power supply would charge the PFN in a shorter time, the PFN was not designed for continuous operation at 1.5 seconds. If indeed the 6-batch beam was needed down the P1 and P2 line, the PFN at MI-52 would need to be completely rebuilt to be reliable at that higher repetition rate. In addition, the magnet would need substantially more cooling of the high voltage load.

Another issue is kicker magnet apertures. They are approximately 1.3 inch V × 3.2 inch H (33 mm V × 81 mm H) for all MI kickers (as shown in Figure 20.3) except at MI-10 where the kicker has an aperture of approximately 1.75 inch V × 3.75 inch H (44 mm V × 95 mm H). The kickers at MI-30, MI-52 and MI-60 could be increased to an aperture of approximately 1.55 inch V × 3.5 inch H without magnet or power supply redesign. This is because the physical aperture in the magnetic material is approximately 2.05 inch V × 4.25 inch H. The MI-40 and MI-62 magnets (which are identical) were moved from the old Main Ring and have less room for a larger vacuum chamber. They would probably have to be rebuilt from scratch. Currently, there is a low level effort to investigate replacement materials for the ceramic vacuum chambers. Two possibilities are Pyrex and PEEK (a high temperature plastic). The PEEK alternative would probably fit with the MI vacuum requirements.
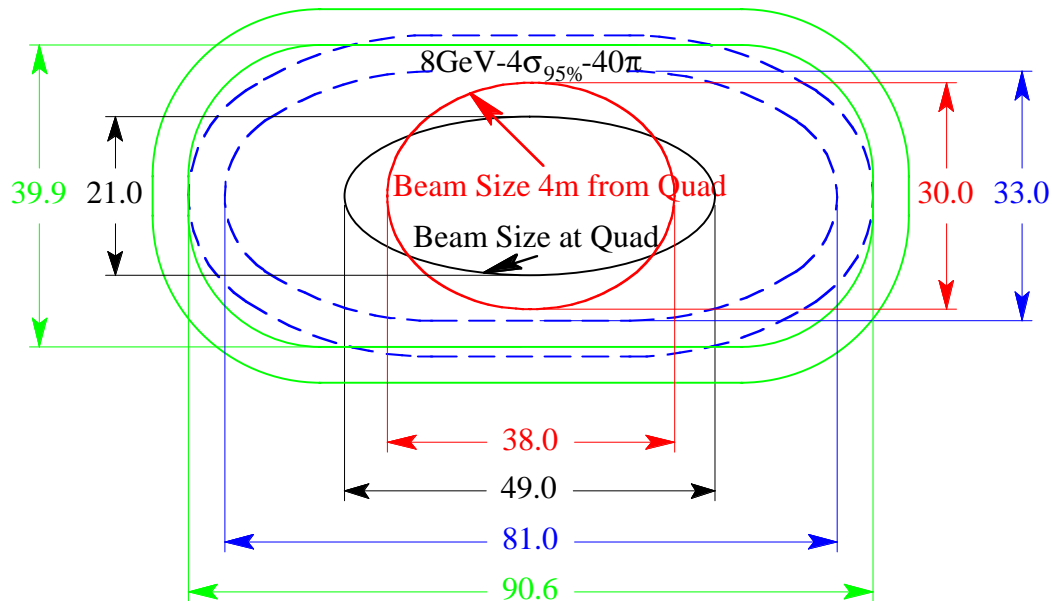
Figure 20.3. Existing (dashed) and proposed (solid) vacuum chamber cross sectionandthe typical beam size at kicker locations (units in mm).
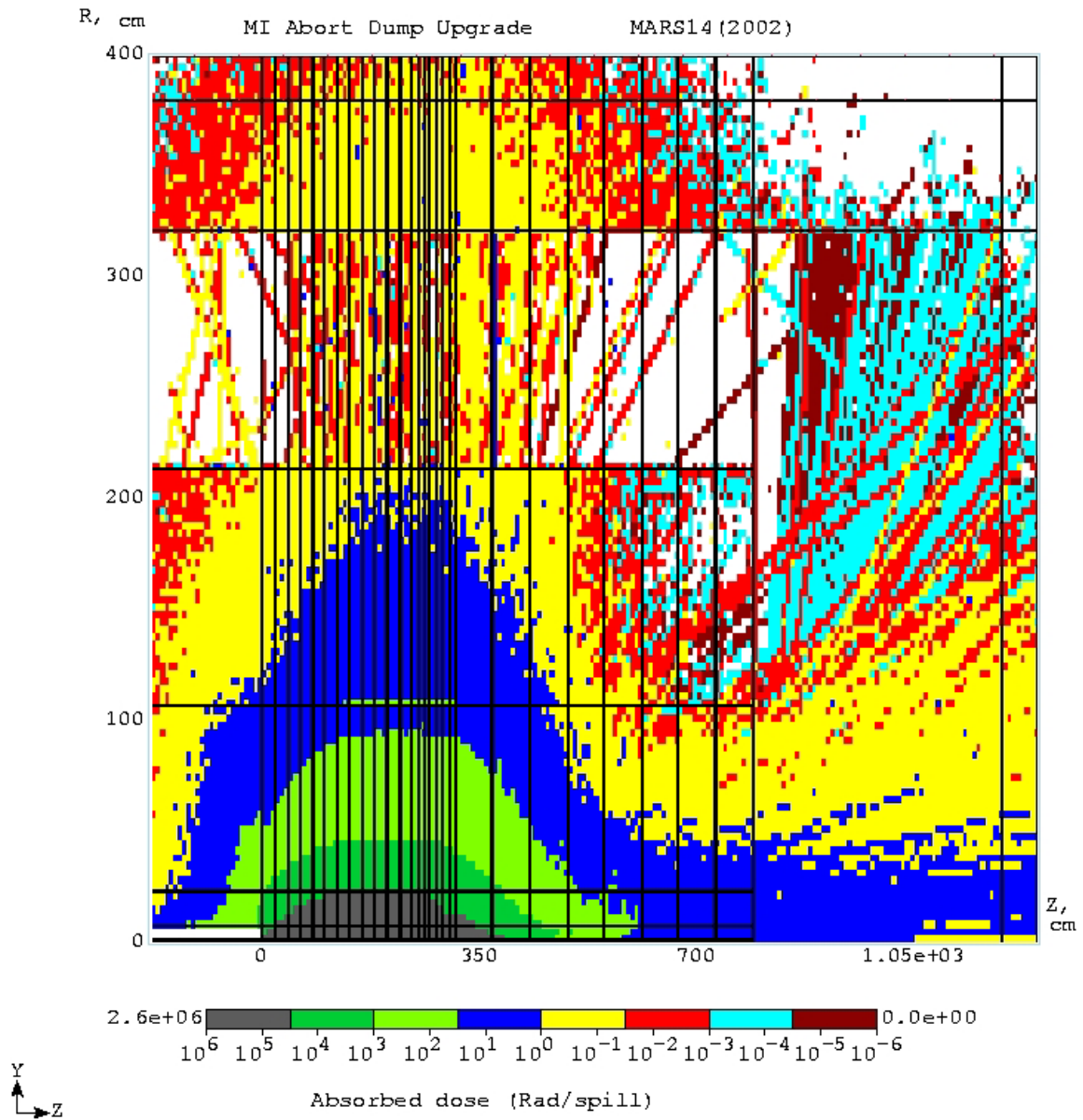
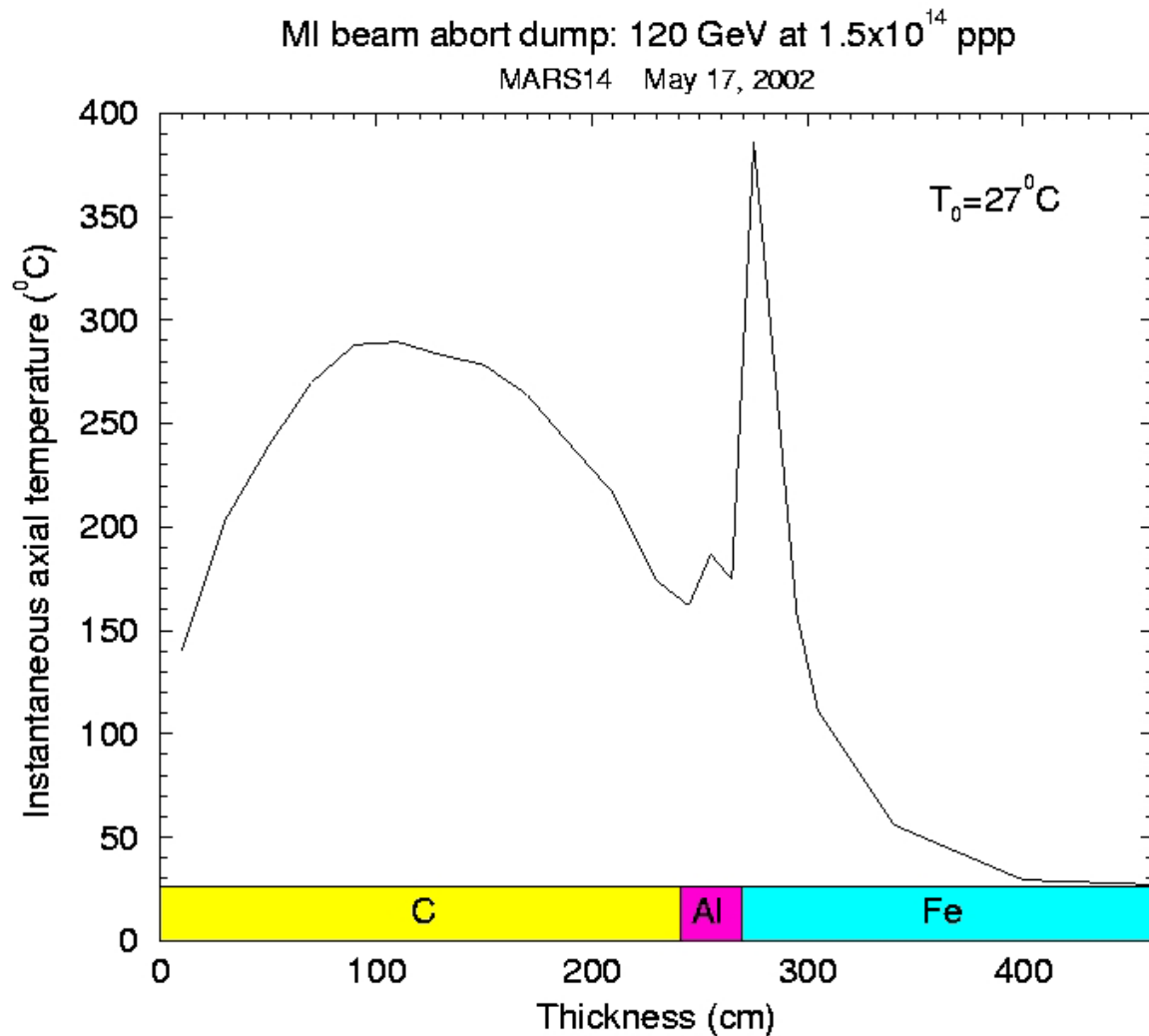## 20.5. Beam Abort Dump

N. Mokhov

With five times more protons on the abort dump, the concerns are instantaneous temperature rise in the graphite core, its integrity and cooling, and radiation levels above grade. These issues have been addressed in detailed Monte Carlo calculations with the MARS code. [1] The following parameters were used in these studies: maximum extraction beam energy of 120 GeV and 1.5×10^{14} protons per pulse with a 1.533 s cycle time, corresponding to 1.9 MW beam power. For a normalized emittance of 40 π mm-mrad, the rms beam spot size at the dump at top energy is $\sigma_x = 4.88$ mm and $\sigma_y = 1.52$ mm. The abort dump, its shielding and enclosure geometry and materials from Ref. [2] were implemented into the MARS model. The graphite core made of 6-in $\times$ 6-in graphite blocks is 2.4 m long, encased in a water-cooled aluminum box. This assembly is surrounded by steel and concrete shielding.

Figure 20.4 shows the calculated absorbed dose distribution in the setup. The corresponding dose on the outer surface of the berm is -- just proportionally -- 5 times higher than now and should not cause a problem. The peak-absorbed dose in graphite can reach 10 Mrad per pulse, which again seems to be acceptable for the assumed beam abort scenario. Figure 20.5 shows the instantaneous temperature after a 120-GeV beam abort on the axis of the beam dump core. The peak temperature in graphite is 290°C, much lower than the ~1000°C in the Tevatron dump graphite core which has been successfully operated since 1980. At the same time the temperature is 186°C in the aluminum box, and 386°C on the axis of the downstream steel. To avoid overheating of the cooling water and structural damage in metals -- especially in a case of successive aborts -- these values need to be reduced by at least a factor of two. This can be provided by increasing the graphite core length (in the upstream open region towards the incoming beam) from 2.4 m to about 3 m. One should also perform a thermal analysis to check if a significant fraction of deposited energy is adequately removed by the existing cooling system prior to the next abort.

Figure 20.4. Isodose contours (Rad per pulse) in the beam abort setup.

Figure 20.5. Maximum instantaneous temperature on the beam axis in the abort dump.

20.6. Controls

M. Shea

20.6.1. Decreased Main Injector cycle time

Decreasing the Main Injector cycle time to 1.5 sec will require a large increase in the rf accelerating system, changes to the main magnet power supplies, and more capacity for the water cooling system. A new gamma-t system would also be added. Although the ring magnet power supplies will be much different, the ramp control will be patterned after the Tevatron and Main Injector ramp controllers. This type of controller was included in PD1.

20.6.2. Main Injector RF Controls

Existing Main Injector high-level rf stations are controlled and monitored using an IRM (Internet Rack Monitor) for each rf station. The option of adding a second power tube to each of the Main Injector rf cavities will require 18 more IRMs and their associated cable interface chassis.

20.6.3. Main Injector Cooling System

Changes in the rf system and magnet power supply will add to the cooling requirements for the Main Injector. In all, the amount of cooling will be roughly double the present capacity. Controls for the present cooling system are PLC (Programmable Logic Controller)-based and PLC controls will be added to accommodate the added cooling equipment.

References

[1]   N.V. Mokhov, "The MARS Code System User's Guide," Fermilab-FN-628 (1995); N.V. Mokhov and O.E. Krivosheev, "MARS Code Status," Fermilab-Conf-00/181 (2000); http://www-ap.fnal.gov/MARS/.

[2]   "Fermilab Main Injector Technical Design Handbook," Fermilab (1994).